Evaluation Of Diesel-Ethanol Blend Studies and Potential to Penetrate the U.S. Transportation Fuel Market

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1. Executive Summary

The first objective of this report is to summarize and discuss laboratory and field trials data obtained in Sweden from engines and vehicles running on diesel-ethanol blend. In the light of the data presented here, the second objective of this report is to determine if lessons from the Swedish experience can help developing a similar R&D project in the United States, and evaluating the potential for diesel-ethanol blend to penetrate the U.S. transportation fuel market.

The data presented and discussed here were generated in Sweden during the project named "The mixed fuel project" which was carried out during the years 1993-1997 under the auspices of the Swedish Transport and Communications Research Board (KFB).[1,2,3,4] The Swedish work was mainly done at Lulea University of Technology, Stockholm University, Lund University, and in collaboration with several private companies including Aspen Petroleum, Volvo Truck, etc. The Swedish project was initiated after some information had been collected in Australia, where a similar project was underway. The Australian project showed some interesting data and developed Dalco, an emulsifier that was subsequently used in the Swedish project. In order to avoid a costly development of a method for blending ethanol in diesel oil, a form of cooperation was established between Australian and Swedish researchers. The content of ethanol in diesel oil used in Australia was 15 % and the investigations in Sweden, discussed further down in this report, show that the ratio 15 % ethanol in MK 1 (an environmentally classified diesel fuel in Sweden) was the best alternative to be used also in the Swedish project.

There are several factors that could be exploited to help ethanol become more competitive with diesel oil, thus enhancing the penetration of the diesel-ethanol blend into the U.S. transportation sector. First, the technology to produce ethanol from low-cost feedstock must be developed and implemented. Secondly, the price of diesel oil must increase to a certain level (unfortunately this does not seem to happen in the foreseeable future). Thirdly, The available data show that using ethanol-diesel blend as a fuel for vehicles designed to be fueled with neat diesel could reduce some of the regulated and unregulated emissions. Especially by using bio-based ethanol in the diesel-

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[1] Egeback K.-E. *Research and field trials with a blend of ethanol in diesel oil.* Report to the Swedish Transport and Communications Research Board. December 1998.

[2] Westerholm, R., Christensen, A., Thörnqvist, M., Ehrenberg, L. and Haupt, D. (1997). Chemical and Biological Characterization of Exhaust Emissions from Ethanol and Ethanol Blended Diesel Fuels in Comparison with Neat Diesel Fuels, KFB-Report 1997:17.

[3] Haupt, D., Nordström, F. Niva, M., Bergudd, L. and Hellberg, S. (1997a). *The Determination of Regulated and some Unregulated Exhaust Gas Components from Ethanol-Blended Diesel Fuels in Comparison with Neat Diesel and Ethanol Fuel.* KFB-information 1997:16.

[4] Alin, L. (1997) Field Trial with Ethanol in Diesel "Diesohol", Final Report, KFB-Report 1997:50

ethanol mixture, emissions of carbon dioxide (a greenhouse gas) would be reduced considerably if the fuel cycle were optimized. In addition to carbon dioxide, emissions of particles are reduced, and even oxides of nitrogen are reduced to some extent. This environmental advantage should be supported by the enactment and enforcement of environmental laws.

However, before the ethanol-diesel blend is applied on a large scale in the U.S., the long-term testing of vehicles running on this fuel mixture is required as well as the development of an efficient large-scale method for blending ethanol into diesel oil. There is also a need to develop more rational production and distribution systems for the ethanol-diesel blend. Finally, there would be an advantage in producing the emulsifier in the United States instead of importing it (like Swedish do from Australia). It seems to be difficult to reach any of these goals unless the fuel becomes more competitive when compared with neat diesel oil.

In order to keep to the possibility of shifting between diesel-ethanol blend and neat diesel oil, it was decided that no adjustment of the engine should be carried out even if it would be beneficial when using diesel-ethanol mixed fuel.

2. Introduction

This report leverages the findings from the Swedish Transport and Communications Research Board (KFB) to evaluate the potential ethanol blended diesel has to penetrate the U.S. transportation fuel market. Some of the major findings included herein are: the status of technology for mixing ethanol in diesel fuel; lab and field trials result on "impact of diesel ethanol blended fuel on CI engine parameters; lab and field trials results of emissions from engines running on diesel-ethanol blended fuel with or without catalyst; characterized health effects of emissions from diesel-ethanol blend engines; and an evaluation U.S. transportation market penetration potential by ethanol–diesel blended fuel.

The KFB research and field trials provided critical data on diesel-ethanol blend mixing technology—in terms of tolerated ethanol content, the need for emulsifier, the need for ignition improver, phase separations, and production, storage, distribution and handling of the blended fuel.

In the aspects of engine parameters, this report investigates findings from the Swedish ethanol-diesel programs on the impacts of the fuel on fuel injection systems, engine wear, efficiency, fuel economy, ignition timing, and drivers' experiences. Laboratory and field data on test procedures, emissions characteristics, etc., are also examined to determine the reliability of the results, and applicability should similar efforts be initiated in the U.S.

In terms of health risks related to the use of ethanol-diesel blended oil, this report provides results from mutagenicity tests and evaluations on the contributions of individual components to the carcinogenic potency of urban air pollution.

These findings and data, including U.S. diesel and ethanol production, diesel prices, estimated diesel-ethanol prices, and benefits (environmental, economic, legislative, technological) are used to determine what challenges need to be resolved for ethanol-blended diesel to successfully compete in the U.S. transportation market.

3. INVESTIGATION ON THE STATUS OF THE TECHNOLOGY FOR MIXING ETHANOL IN DIESEL OIL

The technical aspects raised when planning the project were primarily concerned with the blending technology since blending ethanol or methanol in diesel oil requires the use of a different method compared with blending an alcohol in gasoline. It was of vital importance that the technology used for mixing the fuel be such that fuel emulsion not separate easily into different fractions and that the fuel droplets be under a certain size. There was also some concern as to whether this fuel mixture would increase the wear and tear of the engine, including the fuel system and the function of the engine.

Aspen Petroleum has prepared a report that summarizes results from a field trial in Gothenburg and experiences gained during a cooperation with a transport company (Göteborgs Lastbilscentral, GLC), a fuel dealer (Transportörsbränsle, TRB) and Volvo Truck. In this report, Aspen Petroleum presents a procedure that must be followed when mixing ethanol into diesel oil (Alin, 1997).[5] In addition, Aspen Petroleum claims that there were no problems with phase separation during the field trial for the emulsified fuels that were mixed by Aspen Petroleum.

Contrarily to the claims by Aspen Petroleum, the work by others[6] shows that, after remaining stable for a certain time, the ethanol-diesel fuel mixture separated into different fractions. These studies have shown that the typical characteristics of the diesel used for mixture, especially the aromatics content of the diesel, has a significant impact on the degree of emulsification of ethanol in diesel. The level of ethanol in the diesel-ethanol blend was also found to be a significant factor for the stability of the mixture. The Australian emulsifier Dalco was used to improve the stability of the mixture, however the use of Beraid (an ignition improver) in the diesel-ethanol fuels seemed to destabilize the emulsion by breaking it down.

In the light of the above mentioned observations, there is an indication that the procedure used for blending the fuels was not efficient enough to result in a stable mixture, thus raising the need to improve the mixing procedure. There also seemed to be a need for a new emulsifier as there still may be a problem with phase separation.

The technique used today for mixing the fuel is rather expensive because both the emulsifier, Dalco, and the diesel fuel used for the emulsion must be heated and "wiped" for 10 hours. A new, simpler method for mixing the fuel by using a new emulsifier may be a good solution giving a lower cost of the ethanol-diesel mixed fuel.

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[5] Alin, L. (1997) Field Trial with Ethanol in Diesel "Diesohol", Final Report, KFB-Report 1997:50 (in Swedish).

[6] Berg, R. (1997). Mixed Fuel Ethanol/Diesel, Stage 1 and 2, KFB- Information 1997-41 (In Swedish).

The discussion below will examine the characteristics of some diesel fuels and address the impact of these characteristics on the properties of the resulting diesel-ethanol mixture.

3.1 Characteristics of ethanol, diesel oil, and diesel-ethanol blend

Table 3-1 shows the most important characteristics of diesel fuels being considered for use in diesel-ethanol mixtures in Sweden and in the United States. In the subsequent sections of this Chapter, the impact of these characteristics on the stability and other properties of the diesel-ethanol mixture will be addressed.

Table 3-1. Specifications for Selected Automotive Diesel Fuels Being Investigated in the U.S. and in Sweden

PROPERTY	U.S. DIESEL#2[7,8]	SWEDISH MK1[9]	SWEDISH MK2[10]	EURO-DIESEL[11]
Density @ 15 °C, kg/m^3	856	813.7	813.8	830.5 (ASTM D 4052)
Cetane number	45.5	50.6	52.7	
Cetane Index	45.8	51.2	49.8	53.3 (ASTM D4737)
Viscosity, 40 °C Mm^2/s, cSt	Min. 1.9 / max. 4.1	1.85	1.69	2.6 (ISO 3104)
Flash point, °C	Min. 52	70	74	71 (ASTM D93)
Cloud point, °C	-11	-37	-44	-7 (ASTM D2500)
CFPP, °C	-15	-43	<-45	-18 (EN 116)
Sulfur, weight ppm	Max. 0.50%	2	5	Max. 25 (ASTM D4294)
Phosphorus, mg/l		<1	<1	
Nitrogen, mg/l		<1	21.9	
Energy content, MJ/l		35.4	35.3	
Energy content, MJ/kg		43.53	43.35	
Aromatics, vol. %		4.12	15.98	
Aromatics, vol.%, mono-		4.05	13.12	

[7] Keith Owen and Trevor Coley, *Automotive Fuels Handbook*. Appendix 2, page 547. Society of Automotive Engineers, Inc. Warrendale, PA. 1990.
[8] Ibid., pp. 325-326, Table 14.2.
[9] Karl-Erik Egeback, *Research and Field Trials with a Blend of Ethanol in Diesel Oil.* Report for Swedish Transport and Communications Research Board. Appendix II. December 1998.
[10] Ibid.
[11] Ibid., Appendix III.

Table 3-1 Continued.

PROPERTY	U.S. DIESEL#2[12,13]	SWEDISH MK1[14]	SWEDISH MK2[15]	EURO-DIESEL[16]
Aromatics, vol.%, di-		0.06	2.84	
Aromatics, 2, 2, poly-		-	0.02	
Olefins, vol.-		2.2	2.8	
Paraffines, vol.%		92	79	
PAC, mg/l		5	33	
Distillation:				
IBP, °C		183.8	190.3	179 (ASTM D 86)
5%, °C		197.9	200.8	
10%, °C		199.4	202.6	198 (ASTM D 86)
20%, °C	239	207.6	208.9	
50%, °C	269	225.0	225.3	267 (ASTM D 86)
65%, °C				285 (ASTM D 86)
85%, °C		263.1	251.5	315 (ASTM D 86)
90%, °C	Min. 282 / max. 338			325 (ASTM D 86)
95%, °C		281.1	264.4	340 (ASTM D 86)
FBP, °C	346			352 (ASTM D 86)
% Recovered 98.6		98.6	98.9	
Color				Green (ASTM D 86)
Water content (ppm wt), mg/kg				26 (K FISCHER PPM)
Water & sediment, vol.%	max. 0.05	-	-	-
Carbon residue on 10% Residuum (%)	max. 0.35	-	-	-
Particulate matter				Trace (Visual)
Appearance				Clear (Visual)

12 Keith Owen and Trevor Coley, *Automotive Fuels Handbook*. Appendix 2, page 547. Society of Automotive Engineers, Inc. Warrendale, PA. 1990.
13 Ibid., pp. 325-326, Table 14.2.
14 Karl-Erik Egeback, *Research and Field Trials with a Blend of Ethanol in Diesel Oil.* Report for Swedish Transport and Communications Research Board. Appendix II. December 1998.
15 Ibid.
16 Ibid., Appendix III.

Table 3-2. Specifications of the main properties of ethanol fuels used in the U.S. and in Sweden

PROPERTY	U.S. PureEnergy	SWEDISH #1	SWEDISH #2
Ethanol type	98.8-99.2% pure	E95	E95
Water content, vol%	0.8-1.2	<6.2	<6.2
Color, Hazen (H)		0-15	0-15
Acidity, as acetic acid, (ppm)		<100	<100
Aldehydes, as acetaldehyde, (ppm)		<20	<20
Density (D20/4), kg/m^3		805-815	805-815
PH (glass electrode)		>5.2	>5.2
Ignition improver: Beraid, vol%		9.0	7.0
Vol% ethanol		88.0	89.5
Denaturant 1, MTBE, vol%		0.5	2.25
Denaturant 2, Isobutanol, vol%		2.5	1.03
Corrosion inhibitor, Promax, vol%		0.025	0.02
Metals, %	0	0	0
Ash-forming constituents, %	0	0	0

Table 3-3. Specifications of selected diesel-ethanol blends being investigated in the U.S. and in Sweden

PROPERTIES	Pure Energy Diesel-Ethanol Blend		SWEDISH DIESEL-ETHANOL BLEND	
Ethanol, vol%	15.0		15.0	
Ash content (%wt)	-		Max. 0.010	(ISO 6245)
Carbon residue, 10% dist (%wt)	0.29	(D4530)	Max. 0.30	(SO 4262)
Cetane index	-		46.0	(ASTM D4737)
Cetane number	43.9	(D613)	49.0	(ISO 5165)
CFPP (°C)	-		Max. −13	(EN 116)
Cloud point (°C)	-6		Max. −3	(EN 23015)
Color	-		Max. 2.0	(ISO 2049)
Copper corrosion, 3 hr @ 50 °C	No. 1a	(D 130)	Max. 1	(ISO 2160)
Density @ 15 °C (kg/m^3)	-		820.0-860.0	(ASTM D4052)
Distillation:				(ISO 3405)
Recov. @ 250 °C (vol%)	-		max. 65	
Recov. @ 350 °C (vol%)	-		max. 85	
Recov. @ 375 °C (vol%)	-		max. 95	
Flash point (°C)	13	(D93)	min. 59	(EN 22719)
Oxidation stability (g/m^3)	-		max. 25	(ASTM D2274)
Particulate matter (mg/kg)	-		max. 25	(DIN 51419)
Sulfur (mg/kg)	-		max. 25	(ASTM D5453)
Water content (mg/kg)	12	(D1744)	max. 25	(ASTM D1744)
Viscosity @ 40 °C (mm^2/s)	-		3.00-4.50	(ISO 3104)
PEC Additive Package (vol%)	up to 5		-	
Distillation Temp. T90, (°C)	311	(D86)	-	
Cetane booster (vol%)	0.25-0.35		-	

Water & Sediment	0 (D1796)	-
Kinematic viscosity (cP)	2.25 (D445)	-
Phase Separation Temperature (°C / °F)	-19 / -2	-

3.2 What type of diesel fuel should be used for the production of diesel-ethanol blend?

The following observations are drawn from the experimental data performed under the auspices of the Swedish Transportation and Communications Board (KFB). According to these observations, the composition characteristics of the diesel fuel used for the diesel-ethanol blend seem to have a significant impact on the stability and performance properties of the resulting diesel-ethanol fuel mixture.

- Ethanol was more easily emulsified in Euro diesel than in MK1. The reason for this may be that the Euro diesel had a higher content of aromatics.
- The ethanol-Euro diesel fuel was considered to be more stable than ethanol-MK 1 and that the reason for this could be that the Euro diesel contains a higher amount of aromatics than does MK1 (unfortunately the content of aromatics in Euro diesel was not analyzed).
- The number of phase separated fuels were less among mixtures with max 15 % ethanol than among mixtures with more than 15 % ethanol. This led to the conclusion that the procedure for mixing the fuels was valid only for mixtures up to 15 % ethanol.

3.3 What level of ethanol content in diesel oil could be tolerated?

The experimental data obtained by Swedish researchers show that:

- Mixed fuels with more than 15 % ethanol in diesel oil decreased the power output of the engine. On the other hand, 15 % and less ethanol in the mixture did not have any clearly noticeable impact on the driveability of the engine.
- According to the results of the investigation the ignition delay is dependent on the content of E95. The investigation of the ignition delay when using 15 % ethanol in MK 1 showed that there is very little increase of the ignition delay at high loads and at a temperature of 120 °C of the intake air to the engine, that there was an 0.03 millisecond (ms) increase of the ignition delay at the same load but an intake air temperature of 40 °C. It was also showed that the ignition delay increased to 0.1 ms at low load and an intake air temperature of 40 °C.

3.4 Is there a need for an emulsifier?

There is a need for an emulsifier in order to control the stability and homogeneity of the diesel-ethanol blend.

- For emulsions with a content of ethanol higher than 15 %, a content of the Australian emulsifier Dalco higher than 3.4 % was needed in order to avoid phase separation. The active substance (of unknown composition) in Dalco was 0.6% and the rest was diesel oil.

  - According to the Consultant R. Berg (project manager for trials concerning ethanol in diesel oil) "we can today (1997) promise a durability of 90 days when using Dalco as emulsifier" i.e. no separation of the mixed fuel will occur within that time.

3.5 Is there a need for an ignition improver in the diesel-ethanol blend?

It was shown that the cetane number decreases when mixing E95 with diesel oil. This raises the need for an ignition improver. However, adding Beraid (an ignition improver) to ethanol seems to destabilize the emulsion especially with MK 1 as a base fuel. Beraid seems to influence the emulsifier in a way that causes the active substance of Dalco to precipitate into a powder that leads to a separation of the emulsion.

3.6 Systems for the production, Storage, distribution, and handling of diesel-ethanol blend

A system of tanks at Falutorget in Göteborg (Sweden) has been used in the project. The storage tanks used have been certified for fire risk class 1 goods and placed underground. The pump was connected to GLC card and computer system. The system has worked satisfactorily. It is, however, recommended that in the future a study should be made for a more advanced system of tanks and distribution systems that meet fire class 1 and are situated above ground and placed at the various customer locations.

Aspen Petroleum assumes that the distribution pumps will be situated at the larger users such as - transport companies, towns, truck centers etc., who are large consumers in themselves and will also sell to other interested parties.

Furthermore, Aspen Petroleum suggests that the distribution system could perhaps be combined with a common bankcard so that filling up can take place over the whole country. No difficulties are expected with a statewide distribution provided that Diesohol receives a positive acceptance on the market.

3.7 Phase separation

There was an indication that the procedure used for blending the fuels was not efficient enough to result in a stable mixture. There is therefore a need to improve the mixing procedure and among other things to expand the mixing time, because one of the problem related to the phase separation seemed to have been too short a time for the stirring of the emulsion.

Non-separation of the studied fuels does not exclude the possibility that "special mixtures" (high content of ethanol) may be unstable. The reason is that there are strong concentration gradients in the phase which has not yet separated in two phases. There seems to be a risk that even fuels which are one-phase at the time of inspection may separate after a certain period of storage.

3.8 Need to control the size of the mixed fuel drop

An analysis of the blended fuel showed that the size of the fuel droplets was between 1 to 20 microns (μm) which showed that the droplets were too large. In the report from this part of the investigation it is stated that the size of the fuel droplets should be less than 1 μm in order to be homogenous, which means that the technique for mixing the fuel should be improved.

4. DISCUSSION OF LABORATORY DATA ON "IMPACTS OF DIESEL-ETHANOL BLEND ON ENGINE PARAMETERS"

4.1 What types of engines and what tests are carried out?

Tables 4-1 and 4-2 show the types of engines and fuels used in the Swedish studies.

Table 4-1 . Engines used for the investigation of different fuels.

	"Diesel engine"	"Ethanol engine"
Type:	DSC 1124	DSE011
No:	5281331	5312879
No. Of cylinders:	6	6
Turbo:	Yes	Yes
Inter-cooler:	Yes	Yes
Cylinder volume:	11 liters (671 cubic in.)	11 liters (671 cubic in.)
Compression relationship:	17:1	24:1
Injection pump:	EDC	Bosch
Effect (ISO net):	180 kW (241 bhp)	191 kW (256 bhp)

The two engines used were Scania compression Ignition (CI), inline 6 turbocharged, inter-cooled engines. Both engines were nearly identical except one was optimized for ethanol fuel. Optimization for running this engine on pure E95 included increasing the compression ratio, and changing the fuel injection system.

Table 4-2. Fuels investigated and exhaust after-treatment concepts.

Fuel	Abbreviation	Catalyst used	Engine
Swedish Diesel Environment Class 1	MK1	-----	DSC 1124
Swedish Diesel Environment Class 1	MK1C	DF-07	DSC 1124
84.4 % Swedish Diesel Environment Class 1 and 15 % ethanol[1] (95%)	MK1E[2)]	-----	DSC 1124
84.4 % Swedish Diesel Environment Class 1 and 15 % ethanol[1)] (95%)	MK1EC[2)]	DF-07	DSC 1124
European Diesel Fuel Quality	EDF	-----	DSC 1124
84.4 % European Diesel Fuel Quality and 15 % ethanol[1)] (95%)	EDFE[2)]	-----	DSC 1124
Ethanol [1](95%) with 7 % Beraid	E7	-----	DSE1101
Ethanol[1] (95%) with 7 % Beraid	E7C	Scania	DSE1101
Ethanol[1] (95%) with 9 % Beraid	E9	-----	DSE1101
Ethanol[1] (95%) with 9 % Beraid	E9C	Scania	DSE1101

[1] Ethanol, E95, consists of 95% ethanol + 5 % water. To E95 2% MTBE and 1% isobutanol are added as denaturents.

[2] 3.4 % Dalco emulsifier was added to all blends.

Comment: The Euro-diesel was blended so as to reflect the specification according to EN 590 and is the same batch as the Euro-diesel used in the studies presented in section 5.1, 5.2 and 5.3 respectively.

4.2 Results of investigation

4.2.1 Impacts on fuel injection system

The investigation of the wear of the two fuel injection pumps (one in-line pump and one rotary pump) showed no increasing wear, compared with the use of neat diesel oil, when the fuel used was 15 % E95, 0.6 % emulsifier and 84.4 % diesel oil. However, the investigation concerning the wear of the engine could not be carried out as planned. Therefore there is a need to study the engine wear before the large-scale use of ethanol in diesel oil is introduced.

4.2.2 Impacts on engine wear

Investigations conducted in order to study the influence on the engine function when using a blend of ethanol in diesel oil, including investigations of impact on the engine wear, were carried out at a Swedish technical university. In order to study the technology of mixing ethanol in diesel oil, a separate subproject was carried out.

The result of this study showed that a 15 % blend of ethanol in diesel oil is the best mixture. There was no negative effect indicated on the engine when using this mixture while a mixture of more than 15 % ethanol had a negative influence on the performance of the engine compared with the use of neat diesel oil.

4.2.3 Impacts on engine efficiency

The increase of the volumetric fuel consumption was measured to be 1.5 % when 15 % of E95 was added to the MK1, which indicated that the engine efficiency was improved.

4.2.4 Impacts on fuel economy

As one would expect, the ethanol and ethanol-diesel mixed fuels had higher fuel consumption than the neat diesels due to the lower energy content of the ethanol fuels. Also, in the case of the neat ethanol fuels, they were tested on the dedicated neat ethanol engine whose fuel injection system had been set to a higher volumetric flow for increased or equivalent power.

Table 4-3. Fuel consumption in g/kWh.

Fuel investigated	Fuel consumption g/kWh
Ethanol with 7 % Beraid (E9)	361
Ethanol with 9 % Beraid (E7)	361
Swedish Diesel Envir. Class 1 (MK1)	236
84.4 % Swedish Diesel Envir. Class 1 (MK1) and 15 % ethanol(MK1E)	247

European Diesel Fuel Quality (EDF)	236
84.4 % European Diesel Fuel Quality (EDF) and 15 % ethanol (95%) (EDFE)	247

The ethanol-diesel mixed fuels averaged less than 5% increase in fuel consumption.

4.2.5 Impacts on ignition delay

The investigation of the ignition delay when using 15 % ethanol in MK 1 (an environmentally classified diesel fuel in Sweden) showed that there is no measurable influence on ignition delay at high loads and at a temperature of 120 °C of the intake air to the engine but there was an 0.03 millisecond (ms) increase of the ignition delay at the same load and an intake air temperature of 40 °C. It was also showed that the ignition delay increased with 0.1 ms at low load and an intake air temperature of 40 °C.

4.2.6 Impacts on engine performance concerning torque and power characteristics

Three interesting observations can be made, according to the author of this report, when studying Figures 4-1 and 4-2 respectively.

MK 1 gave the highest torque and consequently the highest power output;
15 % ethanol in Euro-D (European type diesel fuel) gave a higher torque than 15 % ethanol in MK 1;
15 % ethanol in Euro-D gave the same or slightly higher power output as the neat Euro-D fuel.

It could be said that these observations support the experiences obtained during the field trials discussed in Chapter 5 of this report. The higher power output when using neat MK 1 is possibly a result of a higher content of hydrogen in MK 1 than in the Euro-D fuel. Concerning the power loss, it can also be said that these observations support the experiences obtained during the field trials, i.e. that there was a noticeable power loss when using 15 % ethanol in MK 1.

According to Karl Marforio[17], there is a need to follow up the studies carried out so far on engines, and more work should be undertaken and directed to the following three areas:

- The investigation presented here has been carried out on a new "modern" diesel engine and therefore some older engines should be used in future investigations.

- There is a need to develop an ignition improver that is tolerant to the ethanol mixed diesel fuel.

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[17] Karl Marforio, *Performance and Emissions for Scania DS 11 Diesel Engine Fuelled with a Diesel-Ethanol Mixed Fuel, SMPP Euro Test, KFB-Information 1997:21.*

- There is a need to develop an ignition improver that is tolerant to the ethanol mixed diesel fuel.

- If an ethanol mixed diesel fuel is to be used in small industrial engines and small car engines the viscosity of the fuel should be tested, because these types of engines are equipped with other types of injection pumps than are heavier diesel engines.

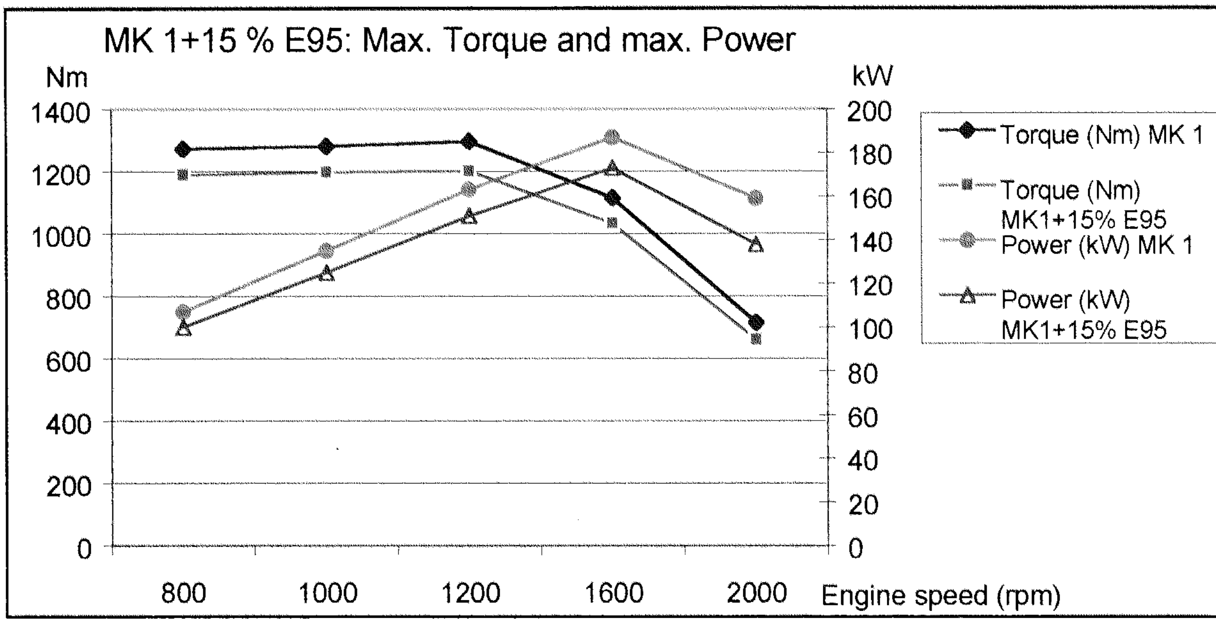

Figure 20. Max. torque and max. power when using MK 1 and MK 1+15 % E95 respectively.

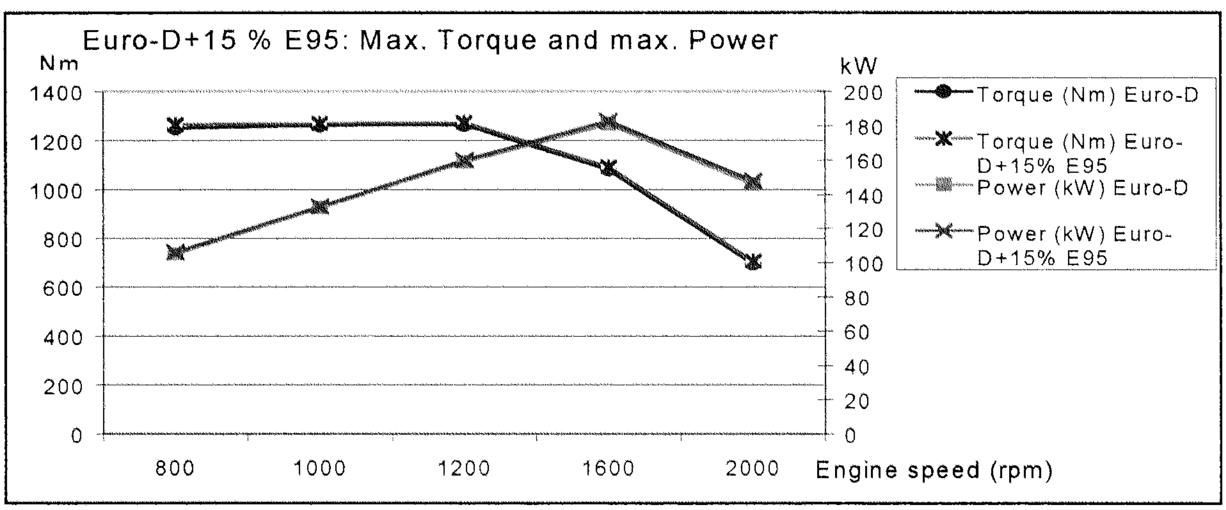

Figure 21. Max. torque and max. power when using Euro-D and Euro-D+15 % E95 respectively.

%, that the smoke emission decreased substantially and that there was no significant influence on the efficiency of the engine when using ethanol in diesel oil.

5. Discussion of Field Trials Data on "Impacts of Diesel-Ethanol Blend on Engine Parameters"

5.1 What types of engines and what tests were carried out?

Table 5-1 shows the types of engines that were used for the field trials. The fleet for the field trial was composed of 20 vehicles.

Table 5-1. Specification for tested vehicles and occasion for the different test series.Vehicle	Lic. No.	Odometer reading At the first test series, ca km	T Test series, week
Scania N112 (bus). Engine: DN	ABZ 260	931 450	w33/95
Volvo FL 614(truck). Engine: TD	GXX 829	223 230	w33/96
Scania 143 (truck). Engine: DSC	ONW 123	563 680	w16/97
Scania D92H (truck). Engine: DSC	GCN 439	206 880	w41/95,v21/96,w36/96/v1
Scania P93M (truck). Engine: DS	BKD 985	113 679	w6/96,v24/96, w40/96

*Natural aspirated engine.

Each test series comprised the following tests:

- 2 tests according to the 13-mode cycle
- 4 tests according to the bus cycle
- Sampling of exhaust for analysis of CO_2[a] and NO_2[b] at the13 mode cycle
- Sampling of exhaust for analysis of CO_2, ethene, propene, methanol, ethanol, formaldehyde and acetaldehyde at the bus cycle. In addition, measurements of the fuel consumption.
- The fuel consumption was also evaluated by using the carbon balance method.

[a] CO_2 is not an emission which is regulated by law in Sweden.

[b] NO_2 is included in NO_xbut no specific standard exist. However, when the exhaust emissions from vehicles operated in city areas are to be characterized it is of vital interest in NO_2 due to its toxicity.

5.2 Results of field trials investigation

The goals for field trials work performed under the auspices of the Swedish Transport and Communications Research Board (KFB) included: work out a basis for a more widespread use of mixed ethanol-diesel fuel; considerably reduce the emission of fossil CO_2; and successively adopt the use of neat (not mixed) bio-ethanol.

In order to fulfill this goal it was important to have a fleet of vehicles operating in a field test where different conditions, such as varying temperatures and topographical conditions among others, could be studied as planned. As the topography and climate conditions vary quite widely in the different parts of Sweden, it was important to divide the vehicle fleet into at least three groups in order to fulfill the basic requirement for the test namely to collect data and experiences from different areas of the country. The following areas were chosen as the main areas for the operation of vehicles: the area of Stockholm; an area in the north of Sweden; an area in the southwest of Sweden.

The fleet for the field trial was composed of 20 vehicles. Personal communication was continuously maintained with the drivers of the vehicles in order to make notes of their experiences concerning the driving conditions of the vehicles and of possible problems during the operation of the vehicles. It was seen to be important that the vehicles were operated in the same manner as common diesel fueled vehicles. The parameters to be noted during the field trials are described below (R. Berg[18]). They include fuel consumption; driving distances/odometer readings; maintenance; type of transports; etc.

5.2.1 Fuel consumption:

No significant changes when driving on roads compared with the use of neat diesel oil. Variations in fuel consumption, which have been noted when operating the vehicles on roads, certainly depend on differences in the manner of driving the vehicle, the mass of cargo carried on the vehicle, the type of road driven on, the weather conditions and the intensity of the traffic. The conclusion in one of the reports to KFB is that the fuel consumption varied from a minor decrease to an increase up to 5 %, when compared with the use of neat diesel oil.

5.2.2 Driving distances/Odometer readings:

The summarized data for the driving distance reported to KFB was 1,879,309 miles (3,024,455 km). No detailed information for individual vehicles was reported. However, every participator has noted the driving distance (odometer reading) when the vehicle was filled-up with fuel. This means that data may be available for those who are interested in a more detailed study of the fuel consumption for the different vehicles.

5.2.3 Maintenance:

Before starting the field trial with the mixed fuel (E15), the fuel filter of the vehicle was changed and this procedure was repeated later on in order to avoid driveability problems caused by a blocked fuel filter. As already pointed out, the changeover to ethanol-diesel fuel in the fuel delivery tank (storage tank) may cause problems from dirt and other contamination washed out from the tank. This problem may also apply in the case of the fuel tank of the vehicle since one of the functions of ethanol is its cleaning function.

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18 Berg, R. (1997) Mixed Fuel Ethanol/Diesel, SSEU's part-project of Stage 2, KFB-Information 1997-40.

5.2.4 Type of transports:

In *the area of Stockholm* 8 vehicles were operated by Stockholm Entreprenad and SKAFAB on E15. The vehicles at Stockholm Entreprenad were used mainly for road maintenance work and for garbage collection in the city and suburbs of Stockholm.

In *the area in the north of Sweden* both buses belonging to the bus company SWEBUS, and trucks belonging to a truck operating company were tested. The buses were used for public transport in the province of Västernorrland, which means that they operate in both city traffic and in the suburbs of the city of Sollefteå. The trucks were used for transport of timber on roads. There is a great difference between summer and winter temperature – from more than +20 to less than -30 °C. During the wintertime there is rather deep snow.

In *the area in the south*west *of Sweden* the fleet of SSEU's field trials contained two heavy-duty vehicles owned by the forestry industry and one truck owned by a farmer's union in the town of Lidköping. The trucks belonging to the forestry industry were used for transport on roads and the same may be the case for the truck belonging to the farmer's union. The difference between the trucks belonging to the forestry industry and the farmer's union is that the transportation distances for the forest industry are long, according to the report to KFB about Stage 2.

5.2.5 The driver's experiences

The driver's experiences are that some of the drivers especially these transporting timber have noted a deteriorated acceleration ability of the vehicle and a lower power rate of the engine related to the E15 fuel. This has not been noticed by the drivers in Stockholm and not the buses in the town of Sollefteå in the north of Sweden.

5.2.6 Impacts on fuel production, storage and distribution systems

The specification of the fuel used is shown in Table 3-3 and consists of 15 % E95, 0.6 % emulsifier and 84.4 % MK 1. Under Stage 2 of the project a firm called Sekab, which supplies ethanol in Sweden, was responsible for the availability of the mixed fuel (E15). Sekab contracted Nordic Tank in the town of Norrköping for the production of the fuel, and the equipment at Nordic Tank was upgraded as well as the storing capacity of the fuel.

The distribution of the fuel to the different areas, where field trials were under-way, was carried out by trucks, which led to a high cost for distribution even if the mixed fuel was distributed together with other petroleum fuels. However one reason for the high distribution cost was that the volumes to be distributed were as small as 2 m^3 and max. 25 m^3. A further reason for the high cost is that the emulsifier called Dalco is supplied from Australia partly mixed with diesel.

Experiences concerning the distribution of fuel show that it became more expensive than calculated prior to the start of the project. Two main problems/concerns appeared to be that:

- The fuel tanks chosen to be used for ethanol mixed diesel fuel were designed and located to be used for neat diesel oil and therefore some modifications had to be carried out for safety reasons. The modifications included: the location of the fuel tank had to be changed as a precaution in the occurrence of fire; filling up the vehicle in-house was not be allowed; the fuel tank had to be protected against collision; and the safety labels on the filling pumps had to be changed.

- Where the fuel tank had been used as storage tank for diesel oil it had to be properly cleaned in order to avoid blockages in the fuel lines and especially in the fuel system of the vehicles due to sludge in the fuel tank.

The opinion among these who have been involved in the investigation concerning the use of ethanol-diesel mixed fuel is that there is a need to improve the whole chain of production and distribution of the fuel. After a closer study of the reports distributed by KFB the author[19, 20] of this report is convinced that such an action should be taken by those who are responsible of the production and distribution of the fuel.

5.2.7 Impacts on driveability of the vehicle

The outcome of the field trials was mainly positive concerning the driveability of the vehicles. Only in cases with heavy loaded vehicles some complaints were noted about a loss of engine power which was observed as a slower acceleration of the vehicle. Tests of the vehicles carried out on a chassis dynamometer showed that there was a 6-7 % loss of the top load when comparing the 15 % ethanol mixed fuel with neat diesel oil (MK 1) – at least for some of the vehicles.

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19 Rolf Berg, *Mixed Fuel Ethanol/Diesel, SSEU's part-project of Stage 2, Befri Konsult, KFB-Information 1997-40.*

20 Rolf Berg, *Mixed Fuel Ethanol/Diesel, Stage 1 and 2, Befri Konsult, KFB-Information 1997-41.*

6. Discussion of laboratory data on "Emissions from engines running on diesel-ethanol blend fuel with or without catalyst"

6.1 Engines, driving cycles and tests carried out for the investigation of different fuels

The engines used for laboratory testing of emissions were two Scania CI engines (the same as described in section 4.1 of this report).

Table 6-1 Engines used for the investigation of different fuels.

	"Diesel engine"	"Ethanol engine"
Type:	DSC 1124	DSE011
No:	5281331	5312879
No. Of cylinders:	6	6
Turbo:	Yes	Yes
Inter-cooler:	Yes	yes
Cylinder volume:	11litres	11litres
Compression relationship:	17:1	24:1
Injection pump:	EDC	Bosch
Effect (ISO net):	180 kW	191 kW

Table 6-2. Fuels investigated and exhaust after-treatment concepts.

Fuel	Abbreviation	Catalyst used	Engine
Swedish Diesel Environment Class 1	MK1	-----	DSC 1124
Swedish Diesel Environment Class 1	MK1C	DF-07	DSC 1124
84.4 % Swedish Diesel Environment Class 1 and 15 % ethanol[1] (95%)	MK1E[2)]	-----	DSC 1124
84.4 % Swedish Diesel Environment Class 1 and 15 % ethanol[1)] (95%)	MK1EC[2)]	DF-07	DSC 1124
European Diesel Fuel Quality	EDF	-----	DSC 1124
84.4 % European Diesel Fuel Quality and 15 % ethanol[1)] (95%)	EDFE[2)]	-----	DSC 1124
Ethanol [1](95%) with 7 % Beraid	E7	-----	DSE1101
Ethanol[1] (95%) with 7 % Beraid	E7C	Scania	DSE1101
Ethanol[1] (95%) with 9 % Beraid	E9	-----	DSE1101
Ethanol[1] (95%) with 9 % Beraid	E9C	Scania	DSE1101

[1] Ethanol, E95, consists of 95% ethanol + 5 % water. To E95 2% MTBE and 1% isobutanol are added as denaturents.

[2] 3.4 % Dalco emulsifier was added to all blends.

Comment: The Euro-diesel was blended so as to reflect the specification according to EN 590 and is the same batch as the Euro-diesel used in the studies presented in section 5.1, 5.2 and 5.3 respectively.

The fuels investigated in the laboratory testing of emissions were also the same as the described in section 4.1 of this report.

6.2 Tests with or without catalyst

The table below is matrix of the fuels tested, and some of the sampled emissions with and without use of a catalyst for post combustion treatment of emissions.

Table 6-3. Results from the 13-mode tests. Before and after the catalyst.

Fuel →	E7		E9		MK1		MK1E	
Component	Before	After	Before	After	Befor e	After	Before	After
HC (g/kWh)	0.30	0.16	0.31	0.16	0.35	0.18	0.39	0.21
CO (g/kWh)	2.53	0.20	2.44	0.13	0.81	0.12	0.73	0.19
NO_x (g/kWh)	3.43	3.45	3.50	3.48	5.72	5.68	6.03	6.20
NO_2 (g/kWh)	0.39	0.12	0.41	0.20	0.29	0.37	0.58	0.47
NO (g/kWh)	3.04	3.32	3.09	3.30	5.44	5.32	5.46	5.75
CO_2 (kg/kW)	0.64	0.64	0.65	0.64	0.64	0.64	0.63	0.65
NO_2/NOx (%)	11.4	3.80	11.8	5.6	5.1	6.5	9.5	7.5

6.3 Results of the investigation

6.3.1 Regulated exhaust compounds, CO, HC, NO_x and particles

Table 6-4 shows the regulated exhaust components. The emissions from fuels E7C and E9C are almost identical. The addition of ethanol to MK1 and EDF increases the emissions of CO (~40%), HC (up to 20%), NO_x (~3-18%), while particulate emissions are decreased by approximately 35%. Particulate and CO (HC) emissions are reduced by the exhaust after-treatment catalytic device.

Table 6-4. Fuel concept regulated exhaust components CO, HC, NO_x and particulate emissions in mass/kWh, +/- S.D.

Fuel	CO, g/kWh		HC, g/kWh		NO_x, g/kWh		Particulate, mg/kWh	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
E7C	2.4	0.2	0.79	0.02	4.2	0.1	12	2
E9C	2.4	0.1	0.76	0.01	4.2	0.0	12	3
MK1	1.4	0.1	0.68	0.02	6.9	0.2	169	12
MK1C	1.6	0.1	0.77	0.09	6.9	0.3	118	21
MK1E	1.8	0.1	0.80	0.02	7.1	0.3	109	7
MK1EC	1.6	0.1	0.81	0.01	7.1	0.1	62	3
EDF	1.3	0.1	0.64	0.02	7.0	0.1	218	27
EDFE	1.9	0.1	0.65	0.01	7.2	0.2	141	15

Table 6-5 Federal Emissions Standards for Heavy-Duty Truck Diesel Engines (g/kW-hr)

Pollutant	**1998 - 2003**	**2004+**
NO x	4.0	NO x + NMHC or 3.35 NO x + NMHC, with cap of 0.67 NMHC
HC	1.3	
CO	20.8	20.8
PM	0.10	0.10

Table 6-6 shows NO, NO_2, CO_2 emissions and fuel consumption. The largest fuel consumption was determined for E7C and E9C fuels which is in accordance with previous findings regarding the energy contents of the fuels. Carbon dioxide emissions are fuel independent. NO/NO_2 emissions from the fuels E7C and E9C are almost identical in consideration of the relatively large S.D. The addition of ethanol to MK1 and EDF reduces NO emissions by 6% while NO_2 emissions are increased by approximately 100%. (NO_x emissions increase approximately 3%, Table 6-6). An indication of an increased NO_2 emission from the catalyst may be seen concerning the MK1 fuel.

Table 6-6. Fuel concept, NO, NO_2 and CO_2 emission and fuel consumption in mass/kWh, +/- S.D.

Fuel	NO, g/kWh		NO2, g/kWh		CO_2, kg/kWh		Fuel consumption, g/kWh	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
E7C	3.66	0.06	0.57	0.03	0.71	0.11	514.3	4.9
E9C	3.70	0.03	0.54	0.02	0.77	0.01	513.7	7.0
MK1	6.26	0.20	0.55	0.01	0.74	0.01	355.7	3.4
MK1C	6.07	0.26	0.79	0.08	0.76	0.02	367.1	17.8
MK1E	5.94	0.31	1.06	0.01	0.72	0.01	359.0	2.0
MK1EC	6.35	0.22	0.72	0.15	0.72	0.01	354.2	1.1
EDF	6.64	0.19	0.40	0.14	0.74	0.01	350.7	1.8
EDFE	6.28	0.09	0.95	0.18	0.74	0.01	360.4	2.5

6.3.2 Polycyclic Aromatic Hydrocarbons (PAH)

Table 6-7 shows the particulate associated and semivolatile PAH emissions as the sums of PAH determined i.e. sum PAH particulate and sum PAH semivolatile. There are large differences depending on the selection of fuel concept and catalyst. In general, the use of an oxidizing catalyst reduces the emissions of total PAH.

Table 6-7. Sum PAH emissions in μg/kWh for the different fuels, particulate associated and semivolatile, +/- S.D. and total PAH emission (particulate associated + semivolatile PAH).

Fuel	Sum PAH, part		Sum PAH, semi		Total PAH	Emissions
	Mean	S.D.	Mean	S.D.	Mean	S.D.
E7C	44	20	27	7	70	27

Fuel	Sum PAH, part		Sum PAH, semi		Total PAH	Emissions
	Mean	S.D.	Mean	S.D.	Mean	S.D.
E9C	101	50	32	2	130	51
MK1	347	150	64	28	410	180
MK1C	64	28	19	12	80	40
MK1E	130	2	140	36	270	140
MK1EC	90	50	64	28	160	76
EDF	706	105	1200	525	1900	630
EDFE	698	320	900*		1600*	

*A relatively large sample to sample variation was found, which cannot be explained without additional experiments.

6.3.3 Characterization of the emissions

Characterization of the emissions took place both by means of sampling exhaust gases while driving the vehicles on the chassis dynamometer according to both the 13-mode cycle (stepwise measurements at five different loads at two different constant speeds respectively) and the so-called bus cycle ("Stochastischer Fahrzyklus für Stadtlinien Omni-busse" - a transient cycle with continuous measurements at varying speeds and engine loads). Furthermore, a program was designed for investigations and research on engines at three universities Luleå University of Technology, Stockholm University and Lund University). Samples were taken according to the 13-mode test procedure and also at two different specially designed test cycles.

The complete program for measurements on the vehicles comprised the measurement of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), carbon dioxide (CO_2), particulate, formaldehyde, acetaldehyde, ethene and propene. Besides these measurements, the fuel consumed during the tests was measured and the fuel consumption was calculated.

The complete program for research and investigations on the engines comprised a study of the performance of two engines – one Scania DSC 1124 designed for neat diesel oil and one Scania DSI 11E01 designed for E95 blended with an ignition improver and two denaturants in ethanol (0.5 mass-% MTBE and 2.5 mass-% isobutanol). This part of the program was carried out in order to characterize the emissions in order to compare the use of 15 % ethanol in diesel oil with the use of neat diesel oil and also to compare emission from these two alternatives with the emissions from the neat ethanol DSI 11E01 engine. During this part of the study of the engine performance both regulated and non-regulated emissions were measured. These studies were partly carried out as cooperative work (joint project) between the two universities Luleå and Stockholm. One part of the program comprised an investigation of a Scania DSC 1124 when using four different mixtures of ethanol in diesel oil and the objective of the investigation was primarily to study the performance of the engine but also the regulated emissions. This part was carried out under the responsibility of Lund University.

The results from the emission measurements on the vehicles, according to both the 13-mode and the bus cycle, gave a general picture of the effect on the emissions and showed the following:

For emission measurements according to the 13-mode cycle on vehicles using neat diesel oil or ethanol-diesel mixed fuel the following results were obtained;

- the emission of carbon monoxide (CO) was somewhat reduced, when using blended fuel compared with the use of neat diesel oil, except in the case of one of the vehicles for which the emission was larger when using mixed fuel than when using neat diesel oil. This vehicle was equipped with a catalyst and the effect of the catalyst on the emissions was also evaluated; see below;

- the emission of hydrocarbons (HC) showed a small increase when using blended fuel except in the case of the vehicle with the catalyst (the same vehicle as above), which showed a considerable larger emission when using the mixed fuel than when using neat. The relatively small fluctuations which can be seen in the results are more a sign of diesel oil;

- the emission of oxides of nitrogen (NO_x) was at roughly the same level when using blended fuel short-term variations than an indication of a specific tendency;

- the emission of nitrogen dioxide (NO_2) tended to increase somewhat, but it remained at a low level;
- the emissions of particles were considerably decreased, between 28 % to 55 %. There was a large variation of the reduction when compared with the emission of particles when diesel oil was used (see section 5.2);

- fuel consumption was increased by 6-7 %, i.e. somewhat higher than the increase of fuel consumption reported from the study of the engine.

The effect of the catalyst has been studied for only one of the vehicles and therefore the evaluation should be limited to the results which were found for this vehicle. The results indicate that:

- the emission of CO and HC are greatly reduced. Unfortunately the emissions of CO and HC were high before the catalyst, at least when the vehicle was driven using blended fuel;

- the emission of NO_x and NO_2 tended to be marginally reduced by the catalyst;

- the emission of particulate was reduced by about 36%.

The trend of the results from the emission measurements according to the bus cycle does not in principle differ from that for the results of the tests using the 13-mode cycle in the case of emissions of carbon monoxide and hydrocarbons. Even when using the bus cycle the emissions of these two pollutants were mainly found to be reduced (CO) or increased (HC). Also in the case of the results of the measurements of emissions of oxides of nitrogen, according to the 13-mode cycle, no certain trend can be seen in the results of the measurements according to the bus cycle. The emission of particulate also shows a definite reduction, but even for the bus cycle tests considerably gap between the smallest and the largest reduction (15 % to 56 %).

6.3.4 Emissions of aldehydes (formaldehyde and acetaldehyde)

The emission of formaldehyde and acetaldehyde is affected, in certain cases, when using blended fuel instead of diesel oil, and an extreme values for formaldehyde are a reduction in this emission of ca 40% to an increase of ca 88%. A corresponding effect on the emission of acetaldehyde was also found with extreme values of a reduction of ca 6% to an increase of ca 200%. Large differences were found between the measured vehicles.

<u>For two of the five vehicles tested the following two observations apply:</u>

- For one of the measurement series on vehicle the mixed fuel contained a small quantity (ca 5 %) of RME. The result from the emission measurements using the bus cycle indicated a certain reduction in the NO_x emission by the use of RME. Since RME blended fuel was tested on only one occasion, it is impossible to establish whether this was a stable trend or whether it was a temporary reduction of NO_x. It could therefore be of value to carry out a more accurate investigation of the effect of RME blended into ethanol-diesel fuel.

- The other observation concerns the use of a catalyst. One vehicle was equipped with a catalyst. The catalyst reduced the emission of CO, HC and particulate but had a negative effect on aldehydes, especially acetaldehyde, so that the emission of these increased during the bus cycle. In one case the increased emission of acetaldehyde was from 53 mg/km (without cat.) to 133 mg (with cat.) and in another case it was from 57 to 96 mg/km respectively. The reason for this increase in the emission of aldehydes may be that the engine emits non-combusted ethanol and that ethanol in the exhaust is only partially oxidized in the catalyst due to the relatively low temperature of the exhaust gases when driving according to the bus cycle.

The program for the characterization of emissions has comprised one series of measurements on one bus and two trucks, three series of measurements on one truck and four series of measurements on one truck, i.e. a total of 10 series of measurements on the five vehicles. The measurements were carried out by AB Svensk Bilprovning (Swedish Motor Vehicle Inspection Company), Motortestcenter (MTC) according to an agreement which was established between AB Svensk Bilprovning and the Swedish Transport and Communications Research Board (KFB).

The results of the measurements at Luleå University of Technology on the engines according to the 13-mode procedure can be summed up as follows:

- Regulated emissions were at a rather low level for all of the investigated fuels. None of the fuels investigated exceeded the limit values of the 13-mode test (ECE R49, 1997) namely 1.1 g/kWh for HC, 4.0 g/kWh for CO, 7.0 g/kWh for NO_x. (and 0.15 g/kWh for particles or 0.25 g/kWh for diesel engines with a cylinder displacement <0.7 dm^3 per cylinder and nominal speed >3000 rpm). Unfortunately the emission of particles was not measured at this part of the emission characterization.

- Total hydrocarbon (THC) emissions were low for all of the investigated fuels without catalyst, 0.30-0.39 g/kWh. An effective reduction (about 45-50 percent) in the hydrocarbon emissions was achieved by using a catalyst. However it was observed that THC was slightly higher for the mixed fuels than for the neat diesel fuels. MK 1 seems to be more sensitive in this respect than the Euro diesel.

- NO_x emissions were found to be at rather low levels for the neat ethanol fuels, approximately 3.5 g/kWh, compared with the other fuels. NO_x emissions for the other fuels investigated were 5.7 - 6.1 g/kWh. There was a somewhat higher level of NO_x for MK 1+ ethanol than for neat MK 1. This difference was not observed for Euro diesel without and with ethanol. NO_x emissions were not affected by the catalyst.

- CO emissions from the ethanol fueled engine (about 2.5 g/kWh) were approximately three times higher than those of the other investigated fuels. However, by using a catalyst, an effective reduction in CO-emission was achieved. CO did not increase by adding ethanol to the two neat diesel fuels (MK 1 and Euro diesel). When comparing the tested diesel fuels without and with ethanol a slight decrease of CO can be observed.

- The volumetric fuel consumption (Fc) was higher for the two neat ethanol fuels than for all of the other fuels. When comparing the two diesel fuels without and with ethanol, Fc was 4.7 % higher with ethanol in the diesel fuels. Fuel consumption calculated in energy terms was approximately on the same level for the mixed fuel as for neat diesel oil.

- Formaldehyde and acetaldehyde emissions were higher for the neat ethanol fuels (E7 and E9) than for the other investigated fuels. When carefully studying the results from the analysis of the aldehydes it can be seen that the levels of both formaldehyde and acetaldehyde are higher for ethanol-diesel oil compared with neat diesel oil. It can also be clearly seen that the level of both formaldehyde and acetaldehyde is lowest for Euro diesel.

It should be stressed that all comparisons without and with ethanol in diesel oil are valid for the alternative "without catalyst".

7. Discussion of Field Trial Data on "Emissions from Engines Running on Diesel-Ethanol Blend with or without Catalyst"

7.1 Vehicles, driving cycles and test series carried out

The vehicles used for field trials, as well as the driving cycles and test series carried out are the same as those described in Section 5.1 (including Table 5-1), Chapter 5 of this report.

7.2 Results of the investigation

The aim of the characterization of the emissions was to study the impact on the emissions of a 15 % content of ethanol in diesel oil. Unfortunately the composition of the test fleet was somewhat limited – four Scania vehicles and only one Volvo vehicle. Therefore it is not possible to give a general picture concerning the emissions when using a ethanol/diesel mixed fuel except for a few emissions components like the particles, which are reduced and aldehydes which increase to a certain degree. If ethanol is produced from renewable raw material and the production method and distribution is optimized CO_2 will decrease proportionally to the content of ethanol in the fuel.

7.2.1 Emissions from the use of ethanol-diesel blend in the 13-mode cycle

Table 7-1 shows emission data from the use of diesel-ethanol blend in the 13-mode cycle.

Table 7-2. Results from emission measurements according to 13-Mode cycle.

13 MODE – ETHANOL/DIESEL BLEND									
Vehicle Lic. No.	Fuel	CO g/kWh	HC g/kWh	NOx g/kWh	NO2 g/kWh	PM g/kWh	Fc g/kWh	Test No.	ELAB
ABZ 260	MK1	2,44	0,82	12,7	-	0,27	223	641	
ABZ 260	Etamix	1,89	0,99	12,9	-	0,19	236	643	
Vehicle Lic. No.	Fuel	CO g/kWh	HC g/kWh	NOx g/kWh	NO2 g/kWh	PM g/kWh	Fc g/kWh	Test No.	ASPEN
GXX 829	MK1	2,13	0,42	11,0	0,57	0,32	227	830	
GXX 829	Diesohol	2,03	0,45	11,0	0,62	0,18	243	831	
Vehicle Lic. No.	Fuel	CO g/kWh	HC g/kWh	NOx g/kWh	NO2 g/kWh	PM g/kWh	Fc g/kWh	Test No.	ASPEN
ONW123	MK1	2,02	0,33	12,7	-	0,16	207	985	
ONW123	Diesohol	1,48	0,38	12,4	0,37	0,084	220	990	
Vehicle Lic. No.	Fuel	CO g/kWh	HC g/kWh	NOx g/kWh	NO2 g/kWh	PM g/kWh	Fc g/kWh	Test No.	SSEU
GCN 439	MK1	2,38	0,40	12,5	-	0,26	220	677	
GCN 439	Etamix	2,04	0,39	12,0	-	0,20	234	678	

GCN 439	MK1	2,23	0,39	12,8	0,56	0,24	219	792	W. RME[1]
GCN 439	Etamix	2,34	0,35	13,3	0,69	0,23	234	789	
GCN 439	MK1	2,03	0,36	12,7	0,38	0,09?	219	849	
GCN 439	Etamix	1,75	0,42	12,7	0,50	0,17	234	848	
GCN 439	MK1	2,44	0,4	12,9	0,55	0,26	219	979	
GCN 439	Etamix	1,77	0,37	12,7	0,59	0,186	234	984	

Vehicle Lic. No.	Fuel	CO g/kWh	HC g/kWh	NOx g/kWh	NO2 G/kWh	PM g/kWh	Fc g/kWh	Test No.	SSEU
BKD 985	MK1	0,32	0,15	8,1	-	0,28	219	738	W. cat.
BKD 985	Etamix	0,67	0,31	7,9	-	0,14	234	739	W. cat.
BKD 985	MK1	0,33	0,16	7,5	0,26	0,33	219	807	W. cat.
BKD 985	Etamix	1,05	0,93	7,3	0,18	0,15	234	811	W. cat.
BKD 985	Etamix	2,36	1,1	7,9	0,33	0,22	234	814	W/o. cat.
BKD 985	MK1	0,35	0,16	7,6	0,13	0,29	219	856	W. cat.
BKD 985	Etamix	0,8	0,45	7,5	0,13	0,13	234	861	W. cat.
BKD 985	Etamix	2,11	0,70	7,8	0,31	0,22	234	862	W/o. cat.

Comm: "W. Cat.." = With catalyst, "W/o. cat.." = Without catalyst.

1) With both ethanol and RME in Diesel oil.

7.2.2 Emission data from the use of Ethanol-diesel blend in the bus cycle

The results from tests according to the bus cycle cover both the regulated emissions and aldehydes as shown in Table 7-2. When using the ethanol/diesel fuel the test was repeated so as to get at least two tests for each series. With MK 1 only one test was carried out for each series of tests. The fuel consumption was measured during each test.

Table 7-2. Results from emission measurements according to the bus cycle.

BUS CYCLE								
ABZ 260								
Series No./Fuel	**CO g/km**	**HC g/km**	**NOx g/km**	**PM g/km**	**CO2 g/km**	**FC meas. g/km**	**Formald mg/km**	**Acetald mg/km**
Series1/ MK1	3,03	1,65	21,3	0,30	1091	358	69	34
Serios1/ Etamix	2,60	1,76	22,5	0,23	1088	377	92	66
GXX 829								
Series No./Fuel	**CO g/km**	**HC g/km**	**NOx g/km**	**PM g/km**	**CO2 g/km**	**FC meas. g/km**	**Formald mg/km**	**Acetald mg/km**
Series 1/ MK 1	4,15	0,54	10,7	0,30	693	236	40	19
Series 1/ Etamix	3,07	0,61	10,6	0,19	709	247	75	25
ONW 123								
Series No./Fuel	**CO g/km**	**HC g/km**	**NOx g/km**	**PM g/km**	**CO2 g/km**	**FC meas. g/km**	**Formald mg/km**	**Acetald mg/km**
Series 1/ MK 1	11,32	0,90	18,2	0,52	1152	372	65	40
Series 1/ Etamix	5,75	1,19	19,4	0,23	1127	388	66	61
GCN 439								
Series No./Fuel	**CO**	**HC**	**NOx**	**PM**	**CO2**	**FC meas.**	**Formald**	**Acetald**

	g/km	g/km	g/km	g/km	g/km	g/km	mg/km	mg/km
Series1/ diesel	6,98	0,85	21,3	0,39	1115	341	67	33
Series1/ Etamix	4,34	0,90	21,1	0,33	1088	356	68	44
Series2/ diesel	6,62	0,82	20,1	0,36	1086	347	58	29
Series1/ Etamix	4,04	0,94	20,0	0,21	1072	359	74	42
Series4/ diesel	6,51	0,75	21,1	0,32	1110	343	52	34
Series1/ Etamix	3,46	0,83	20,8	0,19	1084	358	42	32

GCN 439

Series No/Fuel	CO	HC	NOx	PM	CO2	FC meas.	Formald	Acetald
	g/km	g/km	g/km	g/km	g/km	g/km	mg/km	mg/km
Series3/ diesel	4,98	0,51	20,7	0,35	1091	339	67	39
Series 3/ Etamix*	3,66	0,42	18,7	0,29	1046	348	40	35

* RME added

BKD 985

Series No./Fuel/Catalyst	CO	HC	NOx	PM	CO2	FC meas.	Formald	Acetald
	g/km	g/km	g/km	g/km	g/km	g/km	g/km	g/km
Series1/ diesel/ w. cat.	2,30	0,39	11,0	0,36	1043	330	68	48
Series 1/ Etamix/ w.cat.	1,49	0,37	10,7	0,21	1073	366	67	143
Series2/ diesel/ w. cat.	3,39	0,36	10,2	0,46	1160	373	80	48
Series2/ Etamix/ w. cat.	1,66	0,27	13,2	0,17	1239	427	80	133
Series2/ Etamix/ w.o. cat	3,02	0,86	12,2	0,38	1087	376	46	53
Series3/ diesel/ w. cat.	2,75	0,37	10,9	0,38	1105	351	64	40
Series3/ Etamix/ w. cat.	1,33	0,39	11,4	0,16	1065	360	57	96
Series3/ Etamix/ w.o. cat.	3,35	0,97	11,5	0,28	1051	356	77	57

7.2.3 Comments on emissions trends

The results of the investigation of the impact on the emissions of the use of ethanol/diesel fuel, see Tables 7-1 (13-mode cycle) and 7-2 (bus cycle), were as follows for the 13-mode cycle:

- the **emission of carbon monoxide (CO)** decreased somewhat except from the vehicle which was equipped with a catalyst for which it increased; see without and with a catalyst;

- **the emission of hydrocarbons (HC)** increased slightly except from the vehicle which was equipped with a catalyst where the increase was rather large;

- concerning CO and HC it should be noted that: 1) the catalyst used was not designed for a vehicle using a mixture of ethanol in diesel oil; 2) it can be assumed that a significant part of the value representing the HC emissions is not HC but unburned ethanol;

- according to the results there was no clear impact on the **emission of oxides of nitrogen (NO_x)** when changing from the use of neat diesel oil to the mixture ethanol/diesel fuel. The fluctuations of the emission levels which can be seen are not of that magnitude that they show a clear tendency;

- the **emission of nitrogen dioxide (NO_2)** tended to increase, but it was still at a low level;

- the **particulate emissions** decreased considerably, by -28 % to -55%, compared with the particulate emissions when using diesel;

- the volumetric fuel consumption increased by 6-7%.

Unfortunately the **impact on the emissions of a catalyst** was studied on only one vehicle and therefore no definite impact could be reported. However, the following trends are shown by the results:

- the emissions of CO and HC are considerably reduced.
- the emission of NO_x and NO_2 tended to be slightly (NO_x) or significantly (NO_2) reduced by the use of the catalyst.
- the particulate emissions were reduced by approximately 36 %.

In the case of carbon monoxide and hydrocarbons the trend of the results from the emission measurements according to the bus cycle does not differ from the results found when testing according to the 13-mode cycle. Even when using the bus cycle the emission of these two pollutants is reduced. As in the case of the results from measurements of emissions of oxides of nitrogen according to the 13-mode cycle the results according to the bus cycle permit no definite trend to be identified. The emission of particles shows, even here, a definite decrease of from 15% to 56%.

The **emissions of formaldehyde and acetaldehyde** were affected in certain cases when changing from the use of diesel oil to blended fuel and some extreme values for formaldehyde are a decrease of ca 40% to an increase of ca 88%. A corresponding effect on the emission of acetaldehyde is found, i.e. from a decrease of ca 6% to an increase of nearly 200%. Large differences are found between the various vehicles.

8. CHARACTERIZATION OF HEALTH EFFECTS OF EMISSIONS FROM DIESEL-ETHANOL BLEND ENGINES

8.1 Mutagenicity tests

Mutagenicity, Particulate and Semivolatile Compounds:

The mutagenicity of the particulate and semivolatile extracts from the exhaust samples are shown in Table 8-1 and Table 8-2 for the two *Salmonella thyphimurium* tester strains TA98 and TA100 with (+S9) and without (-S9) metabolic activation. By using metabolic activation, indirectly acting mutagenic compounds, i.e. mutagenic metabolites, may be determined in the samples investigated. More information is given in (Westerholm et al., 1997)[21]

Table 8-1. Fuel concept mutagenic activity in krev/kWh (kilo revertants/kWh), particulate associated, mutagenic activity, Strains TA98 and TA100 with (+) or without (-) metabolic activation (S9), +/- S.D.

	TA98-S9		TA98+S9		TA100-S9		TA100+S9	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
E7C	-0.038	0.41	-0.11	0.41	-3.26	1.35*	2.2	1.9
E9C	0.91	0.28*	0.12	0.55	0.099	1.9	0.99	1.6
MK1	2.3	2.2***	12	1.2***	80	4.5***	35	8**
MK1C	4.3	0.6***	3	0.9**	2	4.7	3.4	8.6
MK1E	18	1***	6.6	0.9***	87	4.5***	24	2.5***
MK1EC	2.5	1.3	0.066	0.79	7	2.8*	7.6	3.1
EDF	92	3.3***	83.6	3.9***	142	23***	128	9.5***
EDFE	78	4.8***	65.8	2.8***	264	17***	132	4.2***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 8-2. Fuel concept mutagenic activity in krev/kWh (kilo revertants/kWh), semivolatile associated, mutagenic activity, Strains TA98 and TA100 with (+) or without (-) metabolic activation S9, +/- S.D.

	TA98-S9		TA98+S9		TA100-S9		TA100+S9	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
E7C	0.3	0.33	0.56	0.49	2	2	0.22	1.8
E9C	0.67	0.43	0.2	0.63	0.55	2	0.43	1.6
MK1	13	3.2**	3.9	0.8**	72	13**	36	7.4***
MK1C	1.8	0.7*	0.9	1.4	13	4.7*	7.2	5.9
MK1E	8.2	0.7***	4.2	0.9**	51	9.1***	20	3.8***
MK1EC	27.8	0.6***	3.7	1**	38	3.7***	8.6	4.2
EDF	16.7	4.1**	18.5	4.1***	147	17***	73	7.4***
EDFE	15.2	1.9***	17.2	0.9***	180	10***	73	4.8***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

21 Westerholm, R., Christensen, A., Thörnqvist, M., Ehrenberg, L. and Haupt, D. (1997). Chemical and Biological Characterization of Exhaust Emissions from Ethanol and Ethanol Blended Diesel Fuels in Comparison with Neat Diesel Fuels, KFB-Report 1997:17.

Dioxin Receptor Binding Assay

Table 8-3 shows the dioxin receptor binding activities IC_{50} and IC_{50}-index (IC_{50}-index is defined as $1/IC_{50}$. See (Westerholm et al[22]. for detailed information).

Table 8-3. Fuel concept dioxin receptor binding activity (IC_{50}) given as $mm^3/kWh/mL\ 10^6$ and IC_{50}-index ($kWh\ mL/\ mm^3$) 10^5, particulate and semivolatile associated.

Fuel	Particulate associated		Semivolatile associated	
	IC50	IC50-Index	IC50	IC50-index
E7C	67600	1.5	65200	1.5
E9C	85300	1.2	72300	1.4
MK1	7240	13.8	24600	4.1
MK1C	40000	2.5	nq	nq
MK1E	5260	19	14000	7.1
MK1EC	38400	2.6	26400	3.8
EDF	1440	69	1480	67
EDFE	1560	64	640	156

nq; not quantifiable, i.e. very low activity.

8.2 Cancer risks

In evaluations of the contributions of individual components to the carcinogenic potency of urban air pollution, a considerable part of the total activity has mostly been ascribed to the PAH. This concerns inhaled particulate and semivolatile compounds, but especially uptake via food of PAHs suspected of originating from precipitated particulate material (Törnqvist and Ehrenberg, 1994)[23]. The present data on individual compounds may be commented upon with regard to the contributions to cancer risks of PAH in exhausts from ethanol and diesel fuels, respectively.

Table 8 shows that for diesel fuel (MK1) and mixed diesel-ethanol fuel (MK1E) the catalyst reduces the total PAH emission by a factor 1.7-5.1 depending on the fuel used. A comparison of the catalyst-provided engines shows that the ethanol fuels (E7C, E9C) emit less total PAH (not statistically significant) than the diesel (MK1C) and mixed diesel ethanol (MK1EC) fuels. This would indicate that the neat ethanol fuels are advantageous with respect to the cancer risks associated with PAH. Such a conclusion would be valid if the abundance profiles of PAH of the fuels compared were approximately the same. That this is not the case is evident from the observation that the relative amount of semivolatile, i.e., lighter, compounds is higher in the ethanol containing fuel than in MK1C (see Table 8-3). The unusually high emission of

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[22] Op cit.

[23] Tornqvist, M. and Ehrenberg, L. (1994). *On Cancer risk elimination of urban air pollution.* Environ. Health Perspect. 102, Suppl. 4, pp. 173-182.

semivolatile compounds in exhausts from the European diesel fuel quality, EDF, is not discussed in this context.

At the very low exposure levels of PAH in most air pollution it is expected that the mutagenic potency, and not the promoter capacity, is the primary determinant of the cancer risk (Vaca et al[24]., 1992; Sjögren et al[25]., 1996). As first indicated by Barfknecht[26] et al., (1982) the semivolatile exhaust component fluoranthene is a major mutagenic factor in diesel exhausts, with certain contributions also from 1- and 9-methylphenanthrenes. This is due to a high mutagenic potency (cf. Vaca[27] et al., 1992) combined with a high relative abundance.

Table 8-4 is a summary of the emitted amounts of a few component, extracted from elsewhere (Westerholm[28], et al., 1997). It shows that the emission of fluoranthene is approximately the same from both the ethanol and the diesel fuels. In contrast, the emission factor of 1-methylphenanthrene is considerably lower in the ethanol than in the diesel fuels.

If further work confirms the role of fluoranthene as a major risk factor among the PAH, the risk associated with the PAH fractions from ethanol and diesel fuels would be approximately the same. It may appear difficult to reconcile such a statement with the mutation data (Tables 8-1,8-2) which, throughout, show the lowest mutagenic potency for the ethanol fuels. It should be kept in mind, however, that the high mutagenic potency of fluoranthene has been established in mammalian, including human, cells, and that its effect in bacteria has been more modest. It should further be remembered that in previous studies (Westerholm[29] et al., 1995; Egebäck[30], 1992; Grägg[31], 1995), there is no clear difference in mutagenic potency (Ames test) between ethanol and diesel fuels.

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[24] Vaca, C., Tornqvist, M., Rannug, U., Lindahl-Kiessling, K., Ahnstrom, G. and Ehrenberg, L. (1992). *On the bioactivation and genotoxic action of fluoranthene..* Arch. Toxicol. 66, pp. 538-545.
[25] Sjoren, M., Ehrenberg, L. and Rannug, U. (1997). *Relevance of different biological assays in assessing initiating and promoting properties of polycyclic aromatic hydrocarbons with respect to carcinogenic potency.* Mutat. Res., 358, pp. 97-112.
[26] Barfknecht, T.R., Hites, R.A., Cavalieri, E.L. and Thilly, W.G. (1982). *Human cell mutagenicity of polycyclic aromatic hydrocarbon components of diesel emissions.* In: Lewtas J. (ed.) *Toxicological effects of emissions from diesel engines.* Elsevier, New York, pp. 277-294.
[27] Op Cit.
[28] Op Cit.
[29] Westerholm R., Tornqvist M., Rannug U. and Ehrenberg L. (1995). *Chemical and Biological Characterization of Bioethanol Related Exhaust Emissions Using Two Diesel Ignition Improvers.* Report to the Swedish Communications Research Board. Stockholm University, Stockholm, Sweden.
[30] Egeback, K-E. (1992). *Flottforsok med 32 etanolbusar vid AB Storstockholms Lokaltrafik.* Avgasemissioner fran etanoldrivna bussar, AB Svensk Bilprovning, MTC-rapport. MTC 9056S,Haninge.

Fluoranthene has no affinity to the Ah- (dioxin) receptor, a fact that is probably associated with its lack of cancer-promoting ability (Vaca[32] et al., 1992; Sjögren[33] et al., 1997). Its presence in exhaust is therefore compatible with a low IC_{50} index (Table 8-3).

To conclude, the relatively low emission of PAH from ethanol fuelled engines would indicate a lower cancer risk due to PAH from ethanol as compared with diesel fuels. Nevertheless, the present data stress the importance of considering the PAH profile.

Table 8-4. Data on certain components in exhausts from ethanol and diesel fuels with catalyst (µ/kWh). First figure: particulate, second figure semivolatile compounds; in parenthesis S.D.

Fuel	Sum PAH	Phenanthrene	1-Methyl phenanthrene	Fluoranthene
E7C	44(20),27(2)	5.5(0.5),13.7(3.6)	1.6(0.1),2.7(1.5)	9.6(1.2),1.8(0.5)
E9C	101(49),33(1.4)	6.2(0.2),19.6(2.4)	1.8(0.4),2.2(0.2)	17.6(8.8),1.8(0.3)
MK1C	64(30),19(12)	24.6(2.7),8.5(4.9)	6.4(0.8),0.7(0.3)	9.4(1.7),<0.9
MK1EC	90(48),64(28)	19.4(6.9),25.6(0.8)	10.1(4.8),4.4(0.6)	8.9(4.3),0.3(0.3)

[31] Gragg, K. (1995). *Chemical characterization and biological testing of exhaust emissions from a truck fueled with EC1 and EPEFE reference fuel, AB Svensk Bilproning, MTC-report MTC 9510, Haninge.*
[32] Op Cit.
[33] Op Cit.

9. EVALUATION OF U.S. TRANSPORTATION MARKET PENETRATION BY DIESEL-ETHANOL BLEND

9.1 Annual consumption of diesel fuel in the U.S.

The consumption of diesel fuel by the transportation sector in the U.S. has steadily increased over the past decade. The consumption of ethanol (E95) has increased dramatically, due to legislative efforts and regulations encouraging the production of reformulated gasoline and reformulated diesel to reduce emissions. Table 9-1 shows the estimated annual domestic consumption of diesel, ethanol, and gasoline fuels over the period 1992 – 1998.

Table 9-1. Estimated domestic consumption of diesel, ethanol, and gasoline fuels over the period 1992-1998 (in Thousand Gasoline-Equivalent Gallons)[34]

YEAR	ETHANOLin GASOHOL	ETHANOL E85[a]	ETHANOL E95[b]	DIESEL	GASOLINE[c]
1992	701,000	21	85	23,866,000	110,135,000
1993	760,000	48	80	24,296,630	111,323,000
1994	845,900	80	140	27,293,370	113,144,000
1995	910,700	190	995	28,555,040	115,943,000
1996	660,200	694	2,699	30,101,430	117,783,000
1997	787,800	1,416	2,628	30,776,920	119,232,000
1998	852,500	1,614	2,628	31,758,340	121,614,000

[a] E85: Consumption data include the gasoline portion of the fuel (15%).
[b] E95: Consumption data include the gasoline portion of the fuel (5%).
[c] Gasoline: Consumption data include ethanol in gasohol and MTBE (methyl tertiary butyl ether).

Between 1992 and 1998, diesel consumption has increased approximately 33%. This increase in the consumption of diesel is likely to continue, especially with recent decreases in the cost of petroleum based fuels. Such consumption of diesel would increase the amount of pollutants emitted by the automotive sector—especially smog, PM, NO_x and HC. As federal emission standards become more stringent, ethanol may help heavy-duty vehicles meet and surpass regulated emission levels. Ethanol in diesel oil will reduce particulate emissions compared to neat diesel, and bio-ethanol in diesel oil is perhaps the best approach to reduce the emission of CO_2 into the atmosphere (although CO_2 is unregulated, but it is the major greenhouse gas).

[34] *Alternatives to Traditional Transportation Fuels 1996.* DOE/EIA-0585(96). December 1997.

9.2 Retail price of diesel fuel in the United States

Table 9-2. Retail price of diesel fuel in the U.S. over the period 1980-1996 (in cents per gallon, including tax).[35]

YEAR	1980	1982	1984	1986	1988	1990	1992	1994	1996
RETAIL PRICE[a]	101.0	116.0	122.0	94.0	95.0	99.0	106.0	96.0	115.0

[a] Retail prices are in 1996$.

The price of diesel has fluctuated over the past two decades. Diesel reached its highest price in nearly 12 years in 1996, but recent trends indicate that in 1999 the prices of petroleum based fuels are decreasing and will likely continue to do so. The cost of ethanol-diesel blended fuel would have to be competitive to that of neat diesel for the blended fuel to succeed in the market.

9.3 Domestic production of ethanol

Table 9-1 shows that the total consumption of diesel by the transportation sector in 1998 was 31.8 billion gallons, and up 5.5% from 1996. Assuming that the diesel consumed by the transportation sector was composed of 15% ethanol by volume, then there would be a need for approximately 4.8 billion gallons of ethanol. Unfortunately, Table 9-3 below shows that the domestic production of ethanol (as of 1996) would only provide approximately 20% of what would be needed by the heavy-duty vehicles alone.

Table 9-3. Domestic production of ethanol over the period 1978-1996 (in million gallons)[36,37]

YEAR	1978	1980	1982	1984	1986	1988	1990	1992	1994	1996
PRODUCTION	20	80	234	567	798	800	756	1,080	1,280	974

9.4 Estimated retail price of the diesel-ethanol blend in the U.S.

The retail price of diesel-ethanol blended fuel is likely to be much higher than that of neat diesel, and that is mainly due to:

- High production cost of ethanol (need for cheap feedstock & conversion technology)
- Imported emulsifier and ignition improver

[35] U.S.DOE/EIA, *International Energy Annual 1995.* Washington, DC, December 1996, p. 102.

[36] Information Resources, Inc., Washington, DC, 1991.

[37] U.S. DOE/EIA, *Petroleum Supply Monthly.* January 1996, Table D1.

9.5 Potential penetration of U.S. transportation market by diesel-ethanol blend

Technology for the driveability of vehicles fueled with ethanol blended diesel is mature. The challenges that need to be resolved for successful penetration of ethanol-diesel blended fuel include mixing technology, and the economic competitiveness of the mixed fuel.

- There is a need for increased domestic production of ethanol for the fuel mixture to penetrate the market. The consumption currently exceeds the domestic production of ethanol since importing large quantities would not be feasible. Improvement in feedstock development and conversion technology will gradually increase the deployment potential of ethanol, and reduce reliability on foreign fuel sources.
- Again, improvements in the production of ethanol (feedstock development, and conversion technology) and domestic production will reduce the price of ethanol, making it a more feasible alternative fuel. Recent trends seem to show a decrease in the price of petroleum based fuels. For ethanol-diesel blended fuel to be competitive, the price of the mixture cannot be much higher than that of neat diesel.
- The domestic fabrication of an emulsifier and an ignition improver would lower the price ethanol-diesel blended fuel, as well as improve performance. The KFB programs imported the emulsifier from Australia, which was expensive, but nonetheless the only option.
- More research is also needed to determine why the ignition improver (Beraid) depleted the function of the emulsifier in the KFB laboratory and field trials.

Emulsifier (mixing technology) and cost are the most significant and persevering problems concerning the ethanol-diesel blend. Should these issues be resolved however, ethanol-diesel blended fuel could become a viable alternative fuel.

10. CONCLUSION

10.1Overall findings

10.1.1 Discussion of problems which occurred when mixing ethanol with diesel oil

During the investigation a systematic study was carried out of the formulae for the mixing of the fuels, the amount and date for deliveries, the composition of different fuel mixtures and also an inspection of the barrels in which the fuel was stored.

The conclusions from a study of the technology of mixing ethanol into diesel oil were that:

- Ethanol was more easily emulsified in Euro diesel than in MK 1. The reason for this may be that the Euro diesel had a higher content of aromatics.
- The ethanol-Euro diesel fuel was considered to be more stable than ethanol-MK 1 and that the reason for this could be that the Euro diesel contains a higher amount of aromatics than does MK 1 (unfortunately the content of aromatics in Euro diesel was not analyzed).
- The number of phase separated fuels were less among mixtures with max 15 % ethanol than among mixtures with more than 15 % ethanol. This led to the conclusion that the procedure for mixing the fuels was valid only for mixtures up to 15 % ethanol.
- There was an indication that the procedure used for blending the fuels was not efficient enough to result in a stable mixture. There is therefore a need to improve the mixing procedure and among other things to expand the mixing time, because one of the problem related to the phase separation seemed to have been too short a time for the stirring of the emulsion.
- For emulsions with a content of ethanol higher than 15 %, a content of the Australian emulsifier Dalco higher than 3.4 % is needed in order to avoid phase separation. The active substance (of unknown composition) in Dalco was 0.6% and the rest was diesel oil.
- Non-separation of the studied fuels does not exclude the possibility that "special mixtures" (high content of ethanol) may be unstable. The reason is that there are strong concentration gradients in the phase which has not yet separated in two phases. There seems to be a risk that even fuels which are one-phase at the time of inspection may separate after a certain period of storage.
- Adding Beraid (an ignition improver) to ethanol seems to destabilize the emulsion especially with MK 1 as a base fuel. Beraid seems to influence the emulsifier in a way that causes the active substance of Dalco to precipitate into a powder which leads to a separation of the emulsion.

- According to R. Berg[38] (project manager for trials concerning ethanol in diesel oil) "we can today (1997) promise a durability of 90 days when using Dalco as emulsifier" i.e. no separation of the mixed fuel will occur within that time.

- Referring to the report prepared by Aspen Petroleum (Alin[39], 1997) it is important to follow a certain procedure when mixing ethanol on diesel oil. The procedure to be used is presented in the report. It should also be underlined that no problem with phase separation during the field trial has been reported for the emulsified fuel which were mixed by Aspen Petroleum.

- The investigations at Swedish universities have shown that today the maximum practical content of ethanol in diesel fuel is 15 percent.

10.1.2 Comparison of different fuels with respect to regulated and unregulated emissions

The fuels E7C ("C" stands for catalyst), E9C, MK1, MK1C, MK1E, MK1EC, EDF and EDFE were compared with respect to emission of regulated and unregulated exhaust components; polycyclic aromatic hydrocarbons (PAH), receptor affinity and mutagenicity tests of particle associated and semivolatile compounds, and risk estimates of exhaust components judged to be carcinogenic. The different fuel concepts evaluation parameters are summarized and presented below. It should be stressed that that samples were taken according to the modal driving cycle which was developed at Luleå Technical University.

Table 10-1, which present a ranking of the emissions, shows that E7C and E9C are basically low emission fuels (engine EE), EDFE and EDF are high emission fuels (engine MFE), while other fuels are intermediate with respect to emissions. Using an oxidizing catalyst exhaust after-treatment device a reduction of harmful substances in the exhaust emissions was observed with respect to the present evaluation parameters.

The relatively low emission of PAH from ethanol fuelled engines would indicate a lower cancer risk due to PAH from ethanol than from diesel fuels (MK1C also has relatively low PAH emissions). However, the present data stress the importance of considering the PAH profile.

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[38] Op Cit.
[39] Op Cit.

Table 10-1. Summary. Ranking of the emissions for the different fuel/engine combinations.

Evaluation	Low	Intermediate	Large
CO	MK1, EDF	MK1C, MK1E, MK1EC, EDFE	E7C, E9C
HC	EDF, EDFE	MK1C, MK1, E7C, E9C	MK1E, MK1EC
NO_x	E7C, E9C	MK1;MK1C	MK1E,MK1EC, EDF, EDFE
Particles	E7C, E9C	MK1EC, MK1E, MK1C, EDFE	MK1, EDF
NO	E7C, E9C	MK1E, MK1C	MK1,MK1EC, EDF, EDFE
NO2	EDF, E7C, E9C, MK1	MK1C, MK1EC	MK1EC, MK1E, EDFE
PAH, particle associated	E7C, E9C	MK1C, MK1EC, MK1E, MK1	EDFE, EDF
PAH, semivolatile associated	MK1C, E7C, E9C	MK1, MK1EC, MK1E	EDFE, EDF
Total PAH	E7C,E9C, MK1C	MK1EC, MK1E, MK1	EDF,EDFE
Mutagenicity[a] particle extracts	E7C, E9C	MK1, MK1E, MK1C, MK1EC	EDFE, EDF
Mutagenicity semivolatile extracts	EC7, EC9	MK1EC, MK1E, MK1C, MK1	EDFE, EDF
TCDD receptor affinity[b] particle extracts	E7C, E9C, MK1C, MK1EC	MK1, MK1E,	EDFE, EDF
TCDD receptor affinity semivolatile extracts	MK1C, E9C, E7C	MK1EC, MK1, MK1E	EDFE, EDF

[a] Ames test in Salmonella typhimurium (Biological test). [b] Dioxin receptor binding activity test. (Biological t.)

10.2Benefits

- the predominant advantage of using ethanol in diesel oil is the reduced particulate emissions compared with neat diesel. From the environmental point of view it is beneficial to use ethanol mixed diesel fuel in that the particulate emissions are proven to be reduced.

- the emission of carbon dioxide is reduced if the ethanol used is made from some renewable raw material. Therefore, mixing bioethanol in diesel oil is one quick way to reduce the emission of CO_2 into the atmosphere.

10.3Unresolved problems/concerns

The Swedish work presented in this report strongly supports the proposal that a modification of the method for the production of diesel-ethanol blended fuel is needed. There seems also to be a need for a new emulsifier as there still may be a problem with phase separation. The technique used today for mixing the fuel is rather expensive because both the emulsifier, Dalco, and the diesel fuel used for the emulsion must be heated for a long time (more than 10 hours). A new, simpler method for mixing the fuel by using a new emulsifier may be a good solution giving a lower cost of the ethanol-diesel mixed fuel. Additional concerns are described below:

- During the field trials it was observed that occasionally a vapor lock in the fuel system on one truck had blocked the engine. This problem may be solved by installing a cooler in the fuel system;

- Up to the present time only small batches of the fuel have been mixed and therefore there is a potential to reduce the costs by improving the method so as to reduce the manually mixing of the fuel;

- Since ethanol is a solvent there is a risk that mud or dirt on the walls or somewhere else in the storage tank or vehicle fuel tank will be dissolved and contaminate the fuel filter of the vehicle. It may therefore be necessary to change the filter shortly after starting the use of the mixed fuel;

- There seems to be a risk that even fuels which are one-phase at the time of inspection may separate after a certain period of storage. In order to improve the emulsion, the Swedish Program suggests to develop an equipment specifically designed to heat the components and maintain the right temperature during the production of the emulsifier. It is also important to mix the fuel at the required pressure. However, heating the components may be costly, and it may be more efficient to try to find an alternative and less expensive method;

- The study has shown that the size of the drops in the mixed fuel must be as small as approximately 1 μm in order to avoid a phase separation of the fuel;

- The quality of the fuel with respect to the phase separation can be improved by an improved method for the mixing of the emulsion or by an improved emulsifier.

- More research is also needed to determine why the ignition improver (Beraid) depleted the function of the emulsifier in the KFB laboratory and field trials. Therefore, there is a need to design and develop new ignition improver and emulsifier that can work together without harming the stability of the diesel-ethanol fuel mixture.

- The storage tanks used by the Swedish Program have been certified for fire risk class 1 goods and placed underground. The system has worked satisfactorily. It is, however, recommended that in the future a study should be made for a more advanced system of tanks and distribution systems that meet fire class 1 and are situated above ground and placed at the various customer locations.

- There is a need to study the engine wear before the large-scale use of ethanol in diesel oil is introduced.

10.4 "Is there a future for ethanol/diesel oil in the U.S. transportation sector?

Currently, there is no diesel-ethanol blend on the U.S. transportation sector (despite the fact that some limited experimentation of the use of ethanol in diesel engine has been tried on). Some research effort is being conducted at a very early stage by one U.S. company, the Pure-Energy Corporation. However, the Pure-Energy effort is still in the stage of developing the technology to make the mixed fuel. At the time of righting this report, we have no knowledge of any domestic test using a diesel-ethanol mixture in an engine either on a chassis dynamometer or on highway. In order to evaluate a potential successful penetration of the U.S. transportation sector by a diesel-ethanol blend, it seems appropriate to rely on the experience from foreign programs such as the Swedish program, which has accomplished several hundred thousand miles with engines and vehicles running on diesel-ethanol blend in the labs as well as on the highway under various topographic and climatic conditions.

According to the research data presented and discussed in this report, there seems to be some uncertainties, not so much concerning the driveability of the vehicles, but with regard to the technology for the production of the emulsion and the economy of using the alternative ethanol mixed in diesel oil. Based on these data, we are making the following statements:

1 If implemented today, the ethanol-diesel blend would likely be more expensive per gallon than neat diesel despite the tax credit on ethanol. In addition, fuel consumption is somewhat higher for the mixed fuel compared with diesel oil. The cost of the fuel seems so far to be the greatest barrier for the use of an emulsion of ethanol in diesel oil.

2 There are several factors that could be exploited to help ethanol to become more competitive with diesel oil, thus enhancing the penetration of the diesel-ethanol blend into the U.S. transportation sector. First, the technology to produce ethanol from low-cost feedstock must be developed and implemented. Secondly, the price of diesel oil must increase to a certain level (unfortunately this does not seem to happen in the foreseeable future). Thirdly, the environmental advantage of ethanol should be supported by the enactment and enforcement of environmental laws such as the Clean Air Act Amendments (CAAA) of 1990 and the EPACT. Finally, a rule such as the EPA Complex Model, which imposes stringent restrictions to the composition of the diesel oil (sulfur content, aromatics content, etc.) to be used on the U.S. transportation sector, has the potential to enhance the development and large-scale use of diesel-ethanol blend in the United States.

3 Before the ethanol-diesel blend is applied on a large scale in the U.S., the long-term testing of vehicles running on this fuel mixture is required as well as the development

of an efficient large-scale method for blending ethanol into diesel oil. There is a need to develop more rational production and distribution systems for the ethanol-diesel blend. First of all there would be an advantage in producing the emulsifier in the United States instead of importing it (like Swedish do from Australia). Secondly there is a need to increase the use of the fuel. Thirdly an efficient distribution of the fuel must be organized. It seems to be difficult to reach any of these goals unless the fuel becomes more competitive when compared with neat diesel oil.

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